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As we fall asleep we forget about the future: A quantitative linguistic analysis of mentation reports from hypnagogia

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Abstract

We present a quantitative study of mental time travel to the past and future in sleep onset hypnagogia. Three independent, blind judges analysed a total of 150 mentation reports from different intervals prior to and after sleep onset. The linguistic tool for the mentation report analysis grounds on established grammatical and cognitive-semantic theories, and proof of concept has been provided in previous studies. The current results indicate that memory for the future, but not for the past, decreases in sleep onset – thereby supporting preliminary physiological evidence at the level of brain function. While recent memory research emphasizes similarities in the cognitive and physiological processes of mental time travel to the past and future, the current study explores a state of consciousness which may serve to dissociate between the two.

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KEYWORDS

Memory for the future; mental time travel; sleep onset; hypnagogic; hallucination; dream; REM; non-REM; states of consciousness; phenomenology; subjective experiencek2

Introduction

Sleep onset hypnagogia is the twilight state of human consciousness, marking the transition from waking to sleep. It occurs regularly and spontaneously in healthy humans, and allows researchers to study potential shifts in cognitive functions while waking consciousness fades into sleeping consciousness. Strategic awakenings performed several seconds to several minutes after sleep onset enable us to question participants on their hypnagogic mentation, mentation which would otherwise be forgotten over the course of the ensuing sleep cycles. In mapping cognitive functions on neurophysiological processes in sleep onset we may not only advance our understanding of human mentation, but in the long run also that of its clinical impairments and treatments.

The transition to sleep is described as a continuous series of changes in (brain) physiology rather than an abrupt state change – it has therefore proven difficult to define one point in time at which sleep begins (Ogilvie, 2001). As a person falls asleep, slow electroencephalographic waves first occur locally towards the end of wakefulness. As a person transitions further into sleep, slow waves become global and merge into large, synchronized networks. As the level of cholinergic (arousalpromoting) neuromodulators decreases, cortical neurons enter an on-off mode of firing, first locally and then globally. These global on-off periods occur synchronously, producing a global low-frequency synchronisation of neuronal activity. Accordingly, during sleep onset, the variability of resting state networks decreases (Deco, Hagmann, Hudetz, & Tononi, 2014).

It is assumed that in so far as episodic memories are conceived in sleeping or waking states of consciousness, they exhibit the same neurophysiological correlates (De Gennaro, Marzano, Cipolli, & Ferrara, 2012). It appears that the temporal-parietooccipital junction and ventromedial prefrontal cortex play a crucial role in dream recall (which suggests that they were involved in encoding episodic memories generated during sleep), while hippocampal and amygdaloid structures mediate memories in both sleep and wakefulness (De Gennaro et al., 2012). In comparison to sleep offset mentation, sleep onset mentation has been described as less dreamlike with respect to bizarreness, emotion, and awareness about the current situation (Cicogna, Natale, Occhionero, & Bosinelli, 1998). However, in previous studies, report judges could not detect differences between mentation reports from sleep onset and sleep offset with regard to references to memories (Cicogna et al., 1998). In how far hypnagogic imagery draws from memory input has previously been studied by systematic self-observation procedures in which the investigator observed and analysed his own hypnagogic imagery in spontaneous drowsy episodes during the day (Nielsen, 1995): According to this investigation, four types of memory sources (immediate-, short-, medium-, and long-term) appear to feed into hypnagogic imagery (Nielsen, 1995). Content of sleep onset mentation is believed to draw from episodic memory, as

participants afterwards (once awake) tended to associate the content of sleep onset mentation with specific personal events (Cicogna, Cavallero, & Bosinelli, 1991; Cicogna et al., 1998).

Mental time travel to the past (i.e. remembering past events) and to the future (i.e. imagining potential future events) seem to be two closely related processes (Schacter, Addis, & Buckner, 2007): It is assumed that episodic memories of the past feed into memory for the future, and empirical evidence suggests that a future event can be imagined more vividly and in more detail if the imagination is anchored in an already familiar setting (de Vito, Gamboz, & Brandimonte, 2012; Schacter et al., 2007).

A number of studies further indicate that imagining the future depends on much of the same neuronal structures that are needed for remembering the past, especially prefrontal and hippocampal regions, and that mental time travel in both directions is a function of default mode network (DMN) activity (Hassabis, Kumaran, Vann, & Maguire, 2006; Schacter et al., 2007). The physiological correlates of mental time travel to the past and future may be so closely related that it could prove difficult to determine differences between the two. However, there is indirect evidence which suggests that mental time travel to the past and mental time travel to the future are functions of distinct physiological processes: First, activity patterns within the DMN appear to differ depending on whether participants think about themselves in a present situation, or whether they imagine themselves in a future situation (Andrews-Hanna, 2012). Second, the hippocampus shows greater activity when someone is remembering past episodes as opposed to imagining the future (Abraham, von Cramon, & Schubotz, 2008; Botzung, Denkova, & Manning, 2008; Weiler, Suchan, & Daum, 2010). Third, we could recently show (using the tool also applied in the present study) that DMN disintegration under LSD is connected with reduced mental time travel to the past, but not to the future (Speth, Speth et al., 2016).

Mental time travels to the past and to the future evidently differ with respect to their temporal orientation. However, it has been suggested that the driving factor behind differences in remembering the past and imagining the future may not be the difference in temporal domain (past versus future) but a difference in the degree of imagination required (to picture fictional events versus those which have actually happened, and of which we have episodic past memories; Schacter et al., 2012).

The DMN is a network of hub regions that show strong structural and functional connections which appear to play a role in various meta-cognitive processes (Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010), including episodic memory retrieval and envisioning of the future, which form the two components of mental time travel (Addis & Schacter, 2008; Buckner, Andrews-Hanna, & Schacter, 2008; Schacter et al., 2012; Spreng & Grady, 2010; Wagner, Shannon,

Kahn, & Buckner, 2005). Mental time travel has been found to correlate positively with DMN resting-state functional connectivity (Andrews-Hanna, Reidler, Huang, & Buckner, 2010).

The DMN has been shown to disintegrate (i.e. to exhibit decreased functional connectivity between its components) in sleep (Picchioni, Duyn, & Horovitz, 2013). While the connectivity between the DMN nodes is strongest in wakeful rest, connectivity has been reported to undergo only small changes (Horovitz et al., 2008; Larson-Priora et al., 2009), or no changes at all (Sämann et al., 2011), in sleep onset. In sleep stage 2, the functional connectivity between the posterior cingulate cortex and medial prefrontal cortex is reduced, and decreases further in sleep stage 3 (Sämann et al., 2011; Wu et al., 2012). This connectivity between posterior cingulate cortex and medial prefrontal cortex is thought to be connected to self-awareness (Vogt & Laureys, 2005). In REM sleep however, DMN connectivity increases again (Chow et al., 2013; Wu et al., 2012). This increase in DMN connectivity during sleep could reflect the unique role which REM sleep plays for memory consolidation (e.g. Stickgold & Walker, 2007) and also with regard to dream generation (e.g. Hobson, 2009).

The AIM model (Hobson, Pace-Schott, & Stickgold, 2000) offers a heuristic to predict changes in mental time travel to the future with regard to sleep onset. The model takes into account that non-REM and REM sleep show a decrease in frontal cerebral blood flow (Maquet et al., 1996, 1997) and assumes a hypoactivation of the dorsolateral prefrontal cortex as well as of the orbitofrontal cortex from waking en route to non-REM and REM sleep. The inactivation of frontal regions is considered to be a result of the interaction between two factors, namely state-dependent brain activation patterns and chemical neuromodulation induced by the interaction of aminergic and cholinergic systems (Hobson et al., 2000). Fosse, Stickgold, and Hobson (2001) assume, based on findings from non-REM and REM sleep, that the ratio of aminergic/cholinergic neuromodulation, and consecutively frontal activation, decreases gradually from waking to sleep onset, and to non-REM and REM sleep. They speculate that in order to conceive and sustain thoughts, the brain relies on sufficient aminergic modulation to maintain dorsolateral prefrontal cortical activity. This process supports working memory while suppressing the perception of external stimuli.

While this mechanism is strong in waking, it decreases together with aminergic modulation en route to REM sleep (Fosse et al., 2001). Correspondingly, “normal, wake-like thoughts” (Rowley, Stickgold, & Hobson, 1998: 67) have been shown to decrease – from waking, to sleep onset, to non-REM sleep, and REM sleep (Fosse et al., 2001), as well as during sleep onset – while the frequency of “unusual thoughts” and hallucinations increases (Rowley et al., 1998: 67). What further supports the prediction of the AIM model for sleep onset is that general blood-oxygen-level dependent (BOLD) activity has been shown to decrease from waking to sleep onset –

notably, amongst others, in the frontal lobes and limbic structures, including the hippocampus as well as the occipital lobes (Kaufmann et al., 2006). However, BOLD signal functional connectivity does not decrease within sleep onset, and functional connectivity within the dorsal attention network even increases slightly in light sleep (Larson-Priora et al., 2009).

In summary, this study sets out to investigate mental time travel to the past and future during sleep onset hypnagogia. Mental time travel to the future is investigated as the ability to imagine, simulate, and predict possible future events (Ingvar, 1985; Schacter et al., 2007), while mental time travel to the past involves episodic memories of a particular autobiographical incident or a particular time and place (Tulving, 2002). Fosse, Fosse, Hobson, and Stickgold (2003) note the challenges of using first-person ratings on mental activity, and the participants' differing understandings of episodic memories. Their observation resonates with the recent philosophical debate on the incommensurability of participants' potentially biased explicit assessments of their own mental events versus their implicit knowledge of their own mental events as displayed in their mentation reports (Speth, Speth, & Harley, 2015; Windt, 2013). The current study therefore uses implicit, third person analyses of first person mentation reports, quantifying linguistic indications of memories for the future in reports from sleep onset hypnagogia. Quantitative linguistic analysis is conducted on mentation reports collected at different time intervals prior to and after sleep onset. Indications of memory for the future are quantitatively compared with indications of thoughts about episodic past memories. Linguistic indications of mental time travel to the past and to the future are distinguished from those of imaginations of present scenarios, which could with regard to further research be relevant for the differentiation between mental time travel and such imaginations that are not anchored in an episodic past scenario, or involve mental time travel to the future.

Method

This study investigates if reports from hypnagogia differ in the number of linguistic constructs that indicate memories for the future, as opposed to episodic past memories and thoughts about the present. Three independent judges (2 male, 1 female) were instructed to analyse a database of participants' reports on mental activity during hypnagogia. The report raters were blind in so far as they were not informed from which stage of hypnagogia the individual reports had been collected.

Database Description

The reports stem from a large mentation report database, detailed information on which can be found elsewhere (Rowley et al., 1998; Stickgold, Malia, Fosse, & Hobson, 2001). In short, the database consisted of a total of 150 mentation reports from nightcap-monitored sleep onset. The

reports were conceived while the participants (sixteen undergraduate students, 19 – 26 years of age, 8 male, 8 female) were still awake, or either 15 s, 45 s, 75 s, 120 s, or 300 s after sleep onset. The nightcap allows home setting recordings without an investigator. It detects head and eyelid movements as indicators of sleep onset. Head movement is measured using a mercury switch while eyelid movement is measured with a piezoelectric eyelid sensor. Sleep onset is identified in terms of a 15 s interval with no more than one eyelid movement (Stickgold, Pace-Schott, & Hobson, 1994). A computer attached to the nightcap awoke participants multiple times per night at the different points in time after sleep onset. Participants taped their oral reports themselves.

Quantitative linguistic analysis of mentation reports

Specific linguistic references to memory for the future, episodic past memory, and thoughts about the present were quantified in the participants' mentation reports. For detailed explanations of the linguistic tool please see below, and also compare Fig. 1. In brief, the linguistic tool developed for the quantitative analysis is partly grammatical and partly cognitivesemantic. The grammatical part of the tool is based on linguistic theta theory (Gruber, 2001; Reinhart, 2002; Reinhart & Siloni, 2005) and measures linguistic references to cognitive agency, i.e. grammatical agencies connected to the semantic field of cognition, describing cognitive acts such as thinking, remembering, or planning. It has been used in different versions to successfully link degrees of linguistic references to motor imagery in mentation reports with motor cortical activation of the respective state of consciousness (Speth, Frenzel, & Voss, 2013), to investigate the effect of transcranial direct current stimulation (tDCS) on motor imagery (Speth et al., 2015; Speth & Speth, 2016a), and to measure the number of linguistic indications of auditory verbal hallucinations and inner speech in different states of consciousness (Speth, Harley, & Speth, 2016), as well as to investigate memory for the future across states of consciousness (Speth, Schloerscheidt, & Speth, submitted for publication). The second part of the current tool is based on the cognitive-semantic theory of mental spaces by Fauconnier and Turner (Fauconnier, 1994; Fauconnier & Turner, 1997): The method of analysing future, past, and present mental spaces was developed for this study in order to measure if instances of cognitive agency introduced references to future, past, or present scenarios that were imagined or recalled by the participants relative to the mentation time.

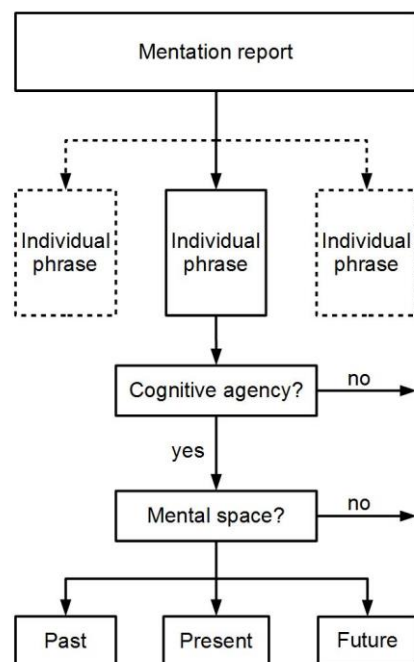


Figure 1: All individual phrases of the mentation reports were analysed with regard to cognitive agencies introducing mental spaces for the past, present, or future.

Analysis of mental spaces hosting past, present, or future scenarios

In linguistic theta system theory, the initiator of an event takes on a specific thematic (theta) role within a sentence or phrase. He or she is the *agent* who performs an action. In the phrase “Mimi throws a ball”, *Mimi* is the agent. The agent is defined through his or her relationship to the predicate of a phrase: He or she is *performing* the action described by the predicate. Mimi is the one who is *doing something*. The agent is described by a noun phrase, but the agent does not necessarily correlate with the grammatical subject. Consider the following examples, where Mimi is the agent in both (i) and (ii), but the syntactic subject only in the active version (i).

- (i) Mimi opens the box.
- (ii) The box is opened by Mimi.

The current tool focusses on *cognitive agency*, i. e. on grammatical agencies connected to the semantic field of *cognition*, describing cognitive acts such as thinking, remembering, or planning. The following phrases (iii) to (ix) contain examples of cognitive agency as they occur in mentation reports:

- (iii) I was thinking, you know, just thinking about things.
- (iv) I just realized that I missed my Italian class yesterday.
- (v) Trying to figure out what went wrong during my date the other day.

- (vi) Just relaxing, contemplating if I... should I be helping Anna and Jill with the dishes or be at the gym instead of sitting around.
- (vii) Thinking about the people in Africa, and what they must feel like fearing that Ebola virus.
- (viii) Asking myself if Mimi is going to enjoy the party.
- (ix) Wondering if I can ace the exam tomorrow.

Often cognitive agents build what linguists call *mental spaces* (Fauconnier, 1994; Fauconnier & Turner, 1997). The notion of mental spaces is borrowed from the philosophical concept of possible worlds – although mental spaces are understood as essentially cognitive scenarios that are not necessarily attributed a specific metaphysical value, and nor do they have to be logically consistent. Mental spaces can host past, present, and future scenarios. Examples (iv) and (v) present cognitive agencies building a mental space for the past. The cognitive agencies in (vi) and (vii) each host a present mental space, and the cognitive agencies in (viii) and (ix) host mental spaces for the future. Mental spaces are marked via (a) grammatical clues (“*going to* enjoy the party”), (b) immediate semantic clues (“yesterday”, “the other day”, “tomorrow”), or (c) contextual clues (someone is “sitting around” pondering if he or she should rather be active in terms of “helping Anna and Jill” or by being “at the gym” – or someone is picturing the current situation in Africa, contemplating what it must be like for the Africans). In this study, a space built by the cognitive agent is defined as a future, past, or present scenario in relation to the cognitive action carried out during the mentation period on which the participant is reporting.

Report rating instructions

All raters were asked to judge all reports. Raters were given a hard copy of the reports and an instruction manual that explained how to identify instances of cognitive agency and ensuing mental spaces in the reports. The instruction manual contained the brief definitions of cognitive agency and mental spaces given above. Raters were asked to count first person cognitive agencies connected to future, past, or present mental spaces in relation to the cognitive act itself. Raters were informed that the mentation reports were transcribed in a way that the original, natural speech is preserved. They would therefore encounter elliptical, aborted, and grammatically ill-formed sentences, and there would be cases where they would be unsure about their rating decisions. Raters were asked to use their best judgment and decide how to deal with such particular phrases, as not all varieties of cognitive agency and ensuing mental spaces possible in natural speech can be pre-defined.

Statistical analyses

The number of identified instances of mental spaces hosting past, present, and future scenarios was counted for every report, separately for every rater. By calculating the mean rating of all raters for each report, one rating value for past, for present, and for future scenarios was assigned to each report.

One-way analyses of variances (ANOVAs) were conducted to test if the number of past, present, or future scenarios differ between the times of awakening. Effect size was estimated by η^2 . Pairwise Scheffé testing was used post hoc. To ensure that the effects are not a result of mere differences in report length, analyses of covariances (ANCOVAs) with word count as a covariate were conducted. Here, effect size was estimated by partial η^2 . Fisher's least significant difference (LSD) test was used post hoc.

Results

The 150 reports from sleep onset comprised 35 reports conceived while the participant was still awake, prior to sleep onset. A total of 27 reports were conceived 15 s after sleep onset, 20 reports after 45 s, 26 reports after 75 s, 18 reports after 120 s, and 24 reports 300 s after sleep onset. Linguistic samples from reports conceived at the different points in time can be seen in Table 1. Rater 1 identified an average of 1.45 (SD = 1.52), Rater 2 an average of 1.45 (SD = 1.55), and Rater 3 an average of 0.97 (SD = 1) cognitive agencies per report. On average, the three raters identified 1.3 (SD = 1.21) cognitive agencies per report. Cronbach's α for the agreement on the number of cognitive agencies per report was .87.

The number of references to future events changed significantly between the different times of forced awakening ($F(5, 144) = 4.70, p < .001, \eta^2 = .14$). Post-hoc pairwise testing indicated that reports conceived while the participant was still awake ($M = 0.94, SD = 1.42$) did not differ significantly from reports collected 15 s ($M = 0.32, SD = 0.49, p = .110$), and 45 s ($M = 0.33, SD = 0.75, p = .203$) after sleep onset, but differed significantly from reports collected 75 s ($M = 0.18, SD = 0.37, p = .023$), 120 s ($M = 0.13, SD = 0.35, p = .037$), and 300 s ($M = 0.11, SD = 0.85, p = .012$) after sleep onset.

No significant change was observed in the number of cognitive agencies introducing present events ($F(5, 144) = 0.44, p = .818$). Further, there were no significant differences in the number of cognitive agencies introducing mental spaces for the past between the different times after sleep onset ($F(5, 144) = 1, p = .423$).

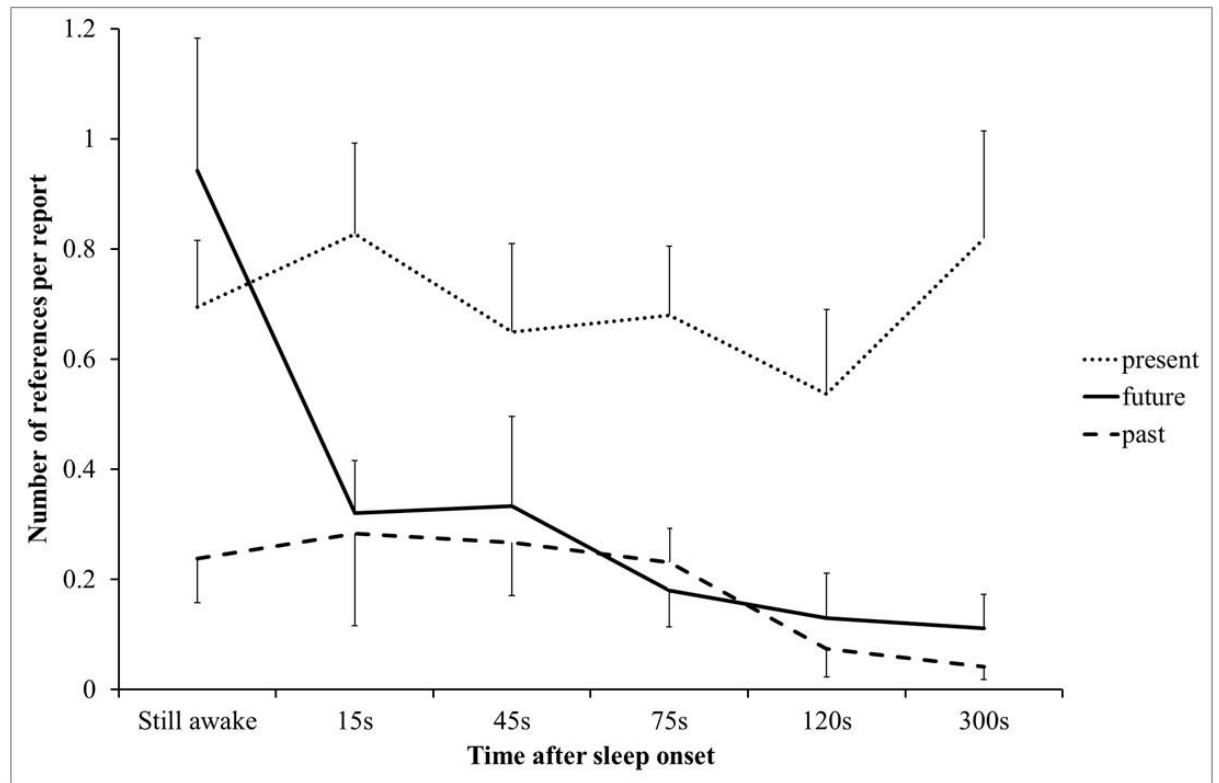


Figure 2: Number of mental spaces for present, future, and past events per report at different times after sleep onset. Error bars show the standard error of the mean; some error bars are omitted for clarity.

After correcting for report length (word count of the report), the number of cognitive agencies introducing mental spaces for the future still differed significantly over the course of sleep onset ($F(5, 143)$, $p = .016$, partial $\eta^2 = .107$). There were more cognitive agencies introducing mental spaces for the future in reports conceived after the participant had still been awake than 15 s ($p = .007$), 45 s ($p = .014$), 75 s ($p = .001$), 120 s ($p = .006$), and 300 s ($p = .003$) after sleep onset.

Table 1: Linguistic samples from reports conceived from sleep onset while participants were still awake, and after 15 s, 45 s, 75 s, 120 s, and 300 s after sleep onset. Linguistic references to mental spaces for the present, future, and past introduced by the cognitive agencies are given.

	Sample	Memory
waking (prior to sleep onset hypnagogia)	I was thinking about when I'm going to make my last day and if I have to actually be in the office on the last day and imagining what personnel was going to say [...] And I think I got to get my wisdom teeth out and I got to make sure I don't leave until April so I can have my insurance through the end of the month.	4 mental spaces for the future
15 s	I think I was thinking of sidewalks, maybe some lamps on it. It was just a blur. I don't know.	1 mental space for the present
	I was thinking about cooking some kind of food and how good it tastes and it was some kind of appetizer dish.	1 mental space for the present

	And I was thinking about like the two of us back in high school and stuff, how we interacted and everything in like a rock band that I was in.	1 mental space for the past
45 s	I'm thinking about the formal tomorrow night and that I; whether I'm gonna look like a giant next to F. and he's gonna look small next to me...	1 mental space for the future
75 s	Thinking that I look pretty good standing on an escalator; riding up an escalator.	1 mental space for the present
	I was thinking about an old friend of mine who I haven't seen in a while... who... and I guess I was seeing us in our past interactions acting together and just hanging out.	1 mental space for the past
120 s	Playing tennis. And it was sunny and warm and we were in Florida 'cause I think we were... golf course... courses... and my Dad was there; I'm not sure if I can remember anything else except that I couldn't play golf at all.	N/A
	I think I was thinking about a hotel. I can't make sen-; I don't really know; some hotel thing.	1 mental space for the present
	And I just want to go to sleep and I was wondering when this onset part ends.	1 mental space for the future
300 s	I was wandering on some kind of hill that was near a port and two minutes or so before I saw like a white light.	N/A
	I was picturing I think a big gorge, in an African Savannah maybe, Oldiva gorge [...] thinking about, you know, elements of an archaeological dig and the sort of thing and you know...	2 mental spaces for the present
	I was thinking about something about people again, but I think like people walking around the room.	1 mental space for the present
	Things are blurry now and it probably involved being in my own house, my dorm, and having people around.	N/A
	Just then I was doing like I was on a beach somewhere exotic so, stretched out on the sand, it was very comfortable.	N/A

Discussion

This study set out to investigate mental time travel to past and future in sleep onset hypnagogia – aiming to understand possible shifts in the human ability to remember past events and imagine, simulate, and predict possible future events as waking consciousness fades into sleeping consciousness. Third person analysis of first person mentation reports from different intervals of sleep onset was used to measure memories for the future, and to quantitatively compare them to episodic past memories as well as thoughts about possible present scenarios. The present study indicates that the current tool objectively and reliably detects linguistic indications of

future, past, and present mental spaces as expressed in the language of mentation reports. It is noted that strictly speaking, the tool measures memories of memories of the future and past, as well as of thoughts about the present, as they occur in offline mentation reports delivered only after the mentation experience itself – a methodological necessity in empirical dream research (Wamsley, 2013; Windt, 2013). An advantage of the quantitative linguistic analysis of mentation reports is that it presents a conservative measure in so far as it looks for differences in the mental events as they are expressed as pre-defined linguistic differences in the reports from different experimental conditions (Speth et al., 2013). The high agreement achieved by the report raters in the current study as well as in related studies (Speth, Speth et al., 2016; Speth, Harley et al., 2016; Speth & Speth, 2016b; Speth et al., 2013, 2015; Speth & Speth, in press), despite the fact that they did not receive intense training or possess a psycholinguistic background, suggests.

The nightcap has been shown to be a reliable tool to investigate sleep onset (Cantero, Atienza, Stickgold, & Hobson, 2002). It is especially useful for large-scale investigations in home settings. However, sleep onset latency determined by the nightcap has been shown to differ by 45 s from sleep onset latency determined by polysomnography in a laboratory setting (Cantero et al., 2002). This should be kept in mind when comparing the present home-based results with potential future results obtained in laboratory settings.

With regard to further improving the method of quantitative linguistic analysis, it might be worthwhile to control not only for the length of the reports (using word count), but to also control for the number of “temporal units” (Foulkes & Schmidt, 1983) in the mentation reports. These temporal units are established by using activity described in the mentation reports, and assigning temporal units to these described activities. However, it would be difficult to use this as an extension of the current tool: In order to determine the temporal unit of a given report, we would first need the participants themselves, and afterwards independent raters to rate the occurrence and then the sequence of temporal units within the mentation reports. The advantage of using this approach could be that this might avoid some uncertainty of other dream studies as to whether the quantity of the content, or the number of words needed to describe given content, is the driving factor for length differences between reports from different sleep states. The downside of using this combined approach can be that the current quantitative method of linguistic analysis was designed as a formal and objective form of analysis with the aim of keeping the raters’ room for interpretation, and their cognitive load, to a minimum – and further as a form of analysis that does not require input from participants in addition to the original report they are asked to deliver. These aims could become compromised if temporal unit scoring is used.

Even though the reports from later points during hypnagogia potentially cover a longer mentation span, they were found to exhibit fewer mental spaces for the future (note that results

were robust to correction for report length). As these results point towards a gradual decline in memory for the future within sleep onset, they can be seen as supporting previous assumptions made based on the AIM model (Hobson et al., 2000) that assume a gradual decrease of physiological activity, namely prefrontal activity, from waking to sleep onset, en route to REM sleep (Fosse et al., 2001). The present results further fit in with physiological evidence on the decrease in frontal and limbic lobe metabolism during sleep onset (Kaufmann et al., 2006), which are brain regions considered fundamental to memory for the future (Flinn, Geary, & Ward, 2005; Schacter et al., 2012; Suddendorf & Corballis, 2007). In the light of (i) previous studies which indicate that the dorsolateral prefrontal cortex and the orbitofrontal cortex play a fundamental role for memory for the future (Flinn et al., 2005; Schacter et al., 2012; Suddendorf & Corballis, 2007) as well as (ii) predictions based on the AIM model that these areas gradually decrease in sleep onset, the present findings appear to provide first evidence that memory for the future decreases during sleep onset hypnagogia. Even though memory for the future is believed to rely on much of the same neuronal structures that are needed for remembering the past, especially prefrontal and hippocampal regions (Hassabis et al., 2006; Schacter et al., 2007), the current results suggest that the number of linguistic indications of episodic past memories, along with thoughts about present scenarios, remains fairly constant throughout sleep onset hypnagogia. As explained in the following, there may be two possible explanations for this observation.

First, it should be noted that episodic past memories were rare to begin with in pre-sleep waking, which may have produced a floor effect – and indeed memory for the future has been shown to be the more salient component of the cognitive function that is mental time travel (Suddendorf, Addis, & Corballis, 2009; Suddendorf & Busby, 2005). Insofar as memories for the future can be considered a crucial part of waking thought, the present results further tie in with earlier findings that “normal, wake-like thoughts” decrease from waking to sleep onset to non-REM sleep to REM sleep, as well as during sleep onset – while the frequency of “unusual thoughts” and hallucinations increases (Fosse et al., 2001; Rowley et al., 1998). The present results suggest that this previously observed decline in “normal, wake-like thoughts” (Rowley et al., 1998: 67) at sleep onset may be closely tied up with the decline of memory for the future, while the number of thoughts connected with past events is relatively low to begin with. This relatively low number of episodic past memories is consistent with previous findings that identify different fragments of recent waking episodes, but rarely find more elaborate replications of waking events in mentation reports from sleep (Fosse et al., 2003; Wamsley, Perry, Djonlagic, Reaven, & Stickgold, 2010; Wamsley & Stickgold, 2011).

A second possible explanation to what appears to be a decline specifically in memories for the future is that at this point in time, phenomenological insight may exceed physiological knowledge

with regard to memory capacities in spontaneous brain activity, and especially spontaneous brain activity at sleep onset. In so far as our preliminary results indicate differences in the shift of memory for the future, in comparison to episodic past memory, during sleep onset hypnagogia, they should be considered in conjunction with emerging differences for these memory structures in waking (Addis, Wong, & Schacter, 2007; Okuda et al., 2003; Schacter et al., 2012).

The current study attempted to differentiate between mental time travel to the past and mental time travel to the future, as well as thoughts about the present. This helps to confirm that the observed changes in memory for the future during sleep onset appear to be driven by a shift in the temporal domain in which thoughts are anchored (i.e. past scenarios or potential future scenarios), as opposed to a decrease in the imagination required: Insofar as thoughts about a possible present situation, and thoughts about potential future situations, do not draw from episodic past memories (of actual events), they should require more imagination (to conceive fictional scenarios). Importantly, the current study saw only a decrease in thoughts about potential future scenarios, while the number of references to thoughts about the present, and about past episodes, remained roughly the same. This is in line with recent research on memory for the future, which demands that studies should seek to differentiate between two possibly unrelated factors: (i) temporal domains (i.e. whether a thought is anchored in the past versus in the hypothetical future), and (ii) mentation revolving around actual versus fictional events (Schacter et al., 2012).

The present study tentatively indicates that sleep onset correlates with a decrease specifically in mental time travel to the future. If the observed decrease in mental time travel to the future were driven by a decrease in imagination (i.e. a decrease in thoughts revolving around fictional versus scenarios actually experienced), we should have seen a decrease not only in mental time travel to the future, but also in thoughts about the present. This study however saw a decrease only in imaginations of the future during sleep onset, while no change was observed in references to mental time travel to the past and thoughts about possible present scenarios (Table 2). In conclusion, this may provide first evidence that the decrease in mental time travel to the future is driven by a decrease in temporal mentation, not by a reduced tendency to imagine (atemporal) fictional events. The quantitative linguistic analysis of mentation reports allowed us to test these difficult latent variables in an indirect way, harnessing participants' implicit knowledge of their mental events as opposed to relying on their differing understanding of the present variables (Fosse et al., 2003).

Table 2: The current results indicate a decrease in mental time travel to the future, but not to the past, during sleep onset. This decrease in mental time travel to the future seems to be driven by a decrease in temporal mentation, as opposed to a reduced tendency to imagine fictional (atemporal) events: While both mental time travel to the future, and thoughts about

the possible present scenarios, require imaginations of fictional events (as opposed to mental time travel to the past, which draws from episodic past memories of events that have actually been experienced), a decrease was observed only for mental time travel to the future.

K2	Temporal domain	Imagination required	Change during the state of sleep onset
Mental time travel to the past	Past	Low (thoughts about actual past events)	No change
Thoughts about possible present scenarios	Present	High (thoughts about imaginary present events)	No change
Mental time travel to the future	Future	High (thoughts about imaginary future events)	Decrease

Insights about regularly occurring hallucinatory states could, in the long run, lead to an improved understanding and treatment of clinical conditions that have been associated with hallucinations as pathological symptoms. The tool presented in the current study allows us to quantify mental time travel during spontaneous mentation. It thus lets us establish changes in the capacity for mental time travel in different states of consciousness as a function of neurophysiological changes. While clearly much further research is necessary, the current tool may therefore be used in future studies to shed more light on the neurophysiological mechanisms of mental time travel, and the conditions for its reduction in connection with memory impairments. The tool could also be used to learn more about psychological disorders which are characterized by an unusual amount of mental time travel to the future, such as generalized anxiety disorder, which can involve anxious apprehension: Patients may engage in a lot of forward thinking in the form of worrying about possible future happenings, and often also show symptoms of depression (Gladstone & Parker, 2003; MacLeod & Byrne, 1996; Miranda & Mennin, 2007; Wells & Carter, 2001). As the current tool is also designed to quantify mental time travel to the past, it could similarly be used to further explore conditions of depression, for which in addition to worrying about future events, a high level of rumination about past events is typical (Berman et al., 2011; MacLeod & Byrne, 1996; McLaughlin, Borkovec, & Sibrava, 2007), or posttraumatic stress disorder, which is characterized by sudden flashbacks to past episodes both in waking and in sleep (Ehlers, Hackmann, & Michael, 2004; Lawrence-Wood, VanHoof, Baur, & McFarlane, 2015). Along these lines, to measure potential treatment success, the present tool was recently used to show that lysergic acid diethylamide (LSD) intake decreases mental time travel to the past in

healthy participants (Speth, Speth et al., 2016) and thus provides first evidence that LSD could be reintroduced into psychotherapy, specifically to treat patients who report excessive rumination.

The advantage of the current tool, in comparison to questionnaires, task paradigms, and other forms of assessments such as patients' descriptions of symptoms in therapeutic settings, is its objectivity and potentially enhanced ecological validity. It lets us quantify mental time travel, to the past or future, as it occurs in phases of spontaneous brain activity during default mode waking and sleep stages across the normal circadian cycle.

By determining the neuronal and cognitive shifts that occur as we fall asleep, we could increasingly learn to dissociate between the components that constitute waking consciousness – such as reflection, anticipation, and planning. Although of course much future research is necessary, this could lead to a better understanding of pathological alterations of these structures in waking, which may ultimately allow for improved clinical treatment.

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